A REPETITIVE CURRENT INTERRUPTER FOR AN INDUCTIVE ENERGY STORAGE CIRCUIT

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Summary

The use of inductive energy storage requires a current interrupter, or 'opening' switch, to divert current into the load. A mechanical switch employing sliding electrical contacts was built and tested in an inductive energy storage circuit. The switch has successfully commutated currents up to 10.5 kA at repetition rates up to 50 Hz. More than 5000 commutations have been achieved with no failures and minimal damage to switch components.

Introduction

Electrical energy storage and pulse compression with an inductive energy store system appears to be attractive in some applications requiring high current pulsed power. Inductive energy stores are particularly well suited for application to electric rail gun systems.[1] Multiple energy pulses must be transferred from the inductor to the load at repetition rates up to a few tens of hertz, current levels ranging from a few hundred thousand amperes to megaamperes and peak voltages of a few kilovolts. Switching has been identified as a critical technology in the development of inductive energy store circuits for repetitively pulsed applications.

One or more characteristics of inductive energy storage circuits places severe requirements on the switch. In repetitive pulse applications, a high duty cycle with high current is imposed on the switch. The switch must therefore, have a low conduction voltage drop. The switch must dissipate a minimum of energy during commutation and must be capable of effectively dissipating this energy with minimal damage to the switch. The switch must therefore, open and develop voltage quickly to commutate current into the load. The switch must be capable of developing adequate standoff voltage capability to withstand rapidly increasing load voltage. The switch must be capable of repeating the cycle at up to 20-30 hertz, with a life of at least several thousand cycles. Finally, for most applications the switch must be compact and low mass.

No switch exists which can satisfy all these requirements. We have designed and tested a laboratory developmental switch which addresses several of the switch requirements for a repetitively pulsed inductive energy storage system. The design conditions were 10.5 kA, a repetition rate up to 50Hz, a 90 percent duty cycle and test durations up to 2 seconds. This paper describes the results of the design and successful testing of the switch.

Switch Design

The switch was designed for low energy dissipation, both low conduction state I^2R losses and low commutation losses. An electromechanical switch which utilizes massive conductors and sliding electrical contacts opening at high speed was selected. The selected switch concept is similar to the 'rail switch' successfully demonstrated by Barber at the Australian National University[1] (ANU). The primary refinement to the ANU switch concept was in modifying the geometry to allow repetitive operation.

The switch design concept is illustrated in Figure 1. A metal disk with an insulating sector is rotated past a pair of stationary current collecting contacts sliding on the disc surface. When the insulating inserts pass between the current collecting contacts, the current path through the rotating disk is interrupted and current is commutated into the load. Low I^2R losses are obtained with appropriate conductor sizing. Commutation losses are reduced by careful integration of the switch and load to minimize inductance.

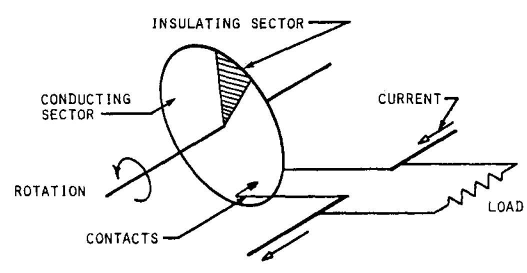

Fig 1. Rotary Switch Concept

A photograph of the switch is shown in Figure 2. The rotor is a 318 mm diameter by 16 mm thick copper disk on a vertical shaft, driven by an electric motor. The maximum rotor speed is 3670 RPM which re-

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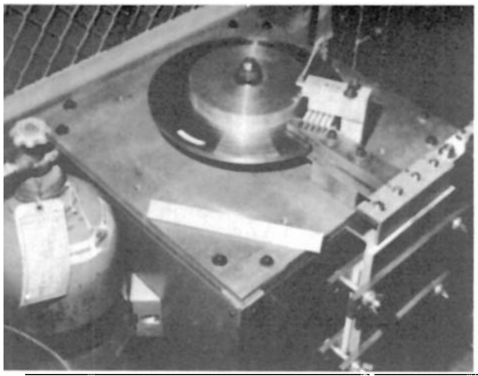

Fig 2. Switch Rotor, Brushes, Brush Actuators and Load Resistor

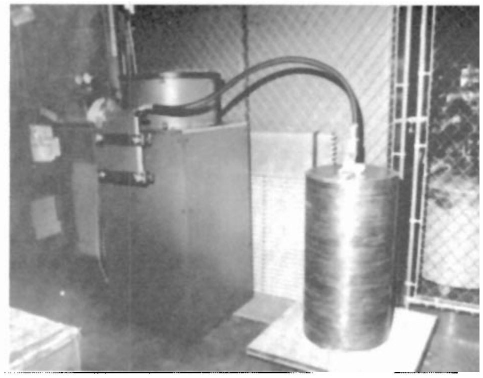

Fig 4. The Complete Switch With Safety Enclosures Installed, Partially Connected to the Energy Storage Inductor.

sults in a surface velocity at the periphery of 61 m/s and a maximum switching frequency of 61 Hz. The insulating inserts were placed into 36 degree included angle sectors milled into each face of the disk. The duty cycle is 90 percent. The current collection brushes are 10 mm cubes of solid Morganite CM1S copper-graphite. Five of these brushes contact each face of the disk, providing a maximum design current level of 10 kA. The brushes are held in contact with the rotor by pressurized air actuated pistons.

Test Apparatus

The rotary switch test circuit is shown schematically in Figure 3. The power supply energizes the energy storage inductor while the switch is in the closed, or conducting condition. When the switch opens, current is commutated into the load. The power supply recharges the inductor when the switch again closes.

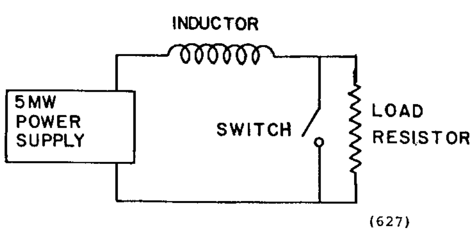

Fig 3. Rotary Switch Test Circuit

Testing was conducted at the Air Force Aero Propulsion Laboratory. The power supply employed was a LING 5 MW, 3 phase rectifier system, with a selectable current up to a maximum rating of 12,000 A. A single layer, 56 turn solenoidal coil with an inductance of 500 μH and a time constant of 64 ms was designed and connected in the test circuit as the energy storage inductor. The load was made of series connected stainless steel plates arranged in a 'folded' geometry to provide a high resistance, low inductance load. The load resistance can be varied from a minimum of 1.4 mΩ to a maximum of 14 mΩ. The load inductance is on the order of 5-10 nH. Figure 4 is a photograph of the inductor, switch, and load arrangement.

The current supplied to the coil, to the switch and to the load were measured using Rogowski coils. The signal outputs from the Rogowski coils were integrated with active electronic circuit integrators. The load voltage was measured differentially. The signals were recorded on a Honeywell Visicorder oscillograph with a maximum bandwidth of 5 kHz. A Tektronix 5000 series storage oscilloscope was used to record the fast transients during commutation.

Test Results

The most important result from this program was the successful repetitive commutation of tens of kiloamps of current into a load representative of an EM launcher. During the course of testing a wide range of switch parameters were investigated. Some of the parameters varied included: switching frequency, current level, load resistance, and contact force. The results of these tests are summarized in Table I and discussed below.

The switch successfully commutated at frequencies ranging from 0.9 Hz to 61 Hz. The only limitation encountered was the speed limitation of the drive motor. Figure 5 shows a typical commutation record at 33.3 Hz and about 5000 A. The figure shows three commutations out of a total of 31 recorded on this test. The sharp leading and trailing pulse edges are typical of all tests.

The commutation voltage depends on the current being commutated and the load impedance. The load resistance was varied over the range of 1.5 to 6.0 mΩ. The shape of the voltage pulse was studied in more detail at the 2000 A and 6.0 mΩ levels. The shape of the leading edge of the voltage pulse was recorded on the Tektronix storage oscilloscope and is illustrated in Figure 6. The shape of the leading edge was exactly as discussed by Windred.[2] The voltage initially rises to about ten volts

TABLE 1. TEST PARAMETERS AND RESULTS

	DESIGN GOALS	DEMONSTRATED PERFORMANCE
Total Commutations	~1000	> 5,000 w/o repair
Frequency	20-50 Hz	0.9-61 Hz
Current	0-10 kA	0.3-10.5 kA
Current Density	0-2.0 kA/cm^2	0-2.2 kA/cm^2
Contact Voltage Drop	0-1.0 V	.2-1.1 V
Max. Energy Per Pulse	3.0 kJ	6.2 kJ
Max. Pulse Power To Load	300 kW	653 kW
Max. Avg. Power To Load	15 kW	65.3 kW
Test Duration	0-2 s	0-3.9 s
Max. Commutation Voltage	30 V	62.4 V
Static Voltage Standoff	1.0 kV	1.0 kV
Load Resistance	1.5-3mΩ	1.5-6.0 mΩ
Load Inductance	5 nH	5 nH
Pulse Width	2-10 ms	1.7-80 ms
Opening Speed	20-50 m/s	0.8-61 m/s
Contact Force	40-250 N	40-320 N

in a fraction of a microsecond as the arc strikes. The voltage rise from ten to 18 volts coincides with the stretching of the arc until the arc voltage reaches the voltage corresponding to the total current times the load resistance. At that point the arc quenches as the current is fully commutated into the load. The switch has operated at commutation voltages up to 62.5 volts.

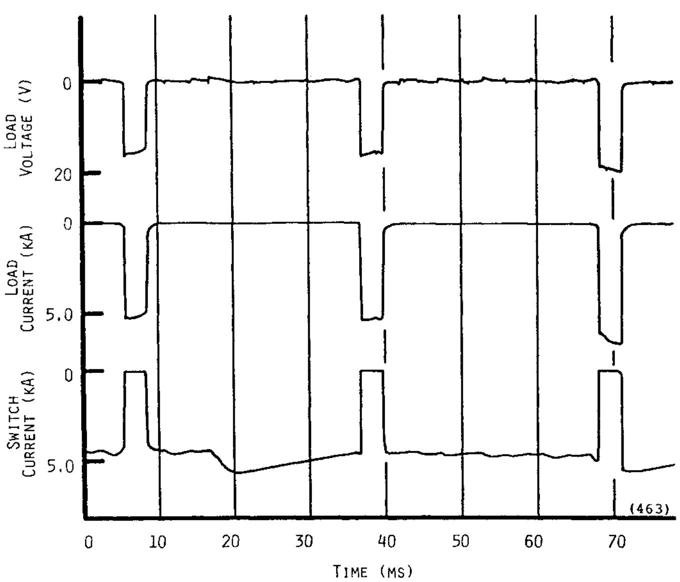

Fig 5. Typical Commutation Events

Using a high voltage supply the standoff voltage of the switch was tested. In the open position the switch was able to standoff over one kilovolt with a current leakage of less than two milliamps.

The switch successfully made more than 5000 commutations at current levels up to 10,500 A with very low wear to the brushes and the rotor. The duration of each of

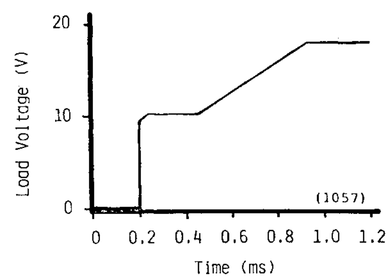

Fig 6. Detail of Commutation Voltage

these tests ranged from 0.5 to 3.9 s, resulting in between 5 and 100 commutations for an individual test. The surface of the copper rotor at the leading edge of the insulating slot eroded slightly but did not affect switch operation.

Two 100 A test runs of several minutes duration were made during attempts to observe the load voltage pulse with the oscilloscope. The results of these two runs were overheating and excessive wear on two of the top brushes (about 50% of the brushes were removed). Another test was made with only one brush on each side of the rotor. A current of 2000 A was run through the switch until failure occurred. The brush straps melted after 3.9 seconds of operation. Commutation continued until brush strap failure. Neither the brushes nor the rotor showed significant degradation or wear due to this test.

Conclusions

The testing results thus far are most encouraging. Comparison of present achievements with original design goals in Table 1 shows that the switch has exceeded expectations in nearly every case. When compared to future application goals there is a long way to go to reach the desired currents. However, even at the present current density these goals should be well within reach. In other areas (frequency,